

THE FIRST LIMITS ON THE ULTRA-HIGH ENERGY NEUTRINO FLUENCE FROM GAMMA-RAY BURSTS

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Draft version January 12, 2013

ABSTRACT

We set the first limits on the ultra-high energy (UHE) neutrino fluence at energies greater than 10^9 GeV from gamma-ray bursts (GRBs) based on data from the second flight of the ANtarctic Impulsive Transient Antenna (ANITA). During the 31 day flight of ANITA-II, 26 GRBs were recorded by Swift or Fermi. Of these, we analyzed the 12 GRBs which occurred during quiet periods when the payload was away from anthropogenic activity. In a blind analysis, we observe 0 events on a total background of 0.0044 events in the combined prompt window for all 12 low-background bursts. We also observe 0 events from the remaining 14 bursts. We place a 90% confidence level limit on the E^{-4} prompt neutrino fluence between 10^8 GeV $< E < 10^{12}$ GeV of $E^4 \Phi = 2.5 \times 10^{17}$ GeV³/cm² from GRB090107A. This is the first reported limit on the UHE neutrino fluence from GRBs above 10^9 GeV, and the strongest limit above 10^8 GeV.

Subject headings: gamma-ray bursts: general - neutrinos

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most powerful explosions in the universe, and are thus considered to be a possible source of ultra-high energy (UHE) cosmic rays. Short-duration bursts are believed to be a result of the collision of two compact objects and long-duration bursts are thought to be beamed emission from the collapse of a high-mass star into a black hole. See Meszaros (2001, 2002) for reviews of the basic theories of GRBs. In the widely-accepted fireball shock model, relativistic plasma in a jet collides either with the surrounding material or with the outflow itself, producing the observed gamma-ray prompt emission through synchrotron and inverse Compton scattering of electrons (Meszaros & Rees 1993). Protons are also thought to be accelerated in these shocks via the Fermi mechanism (Wick 2004; Dermer 2006). These UHE protons then interact with the photons, going through a Δ^+ resonance and producing charged pions which decay, yielding UHE neutrinos (Becker 2008; Halzen & Hooper 2002). The first calculations of this prompt UHE neutrino emission use an E^{-2} proton injection spectrum

with energies up to $E=10^{11}$ GeV, and predict an E^{-4} neutrino spectrum in the UHE regime, with the steepening of the spectrum due to synchrotron cooling of the UHE pions (Waxman & Bahcall 1997, 1999, 2000; Alvarez-Muñiz & Halzen 1999).

The detection of UHE neutrinos from GRBs would support their identification as the sources of the highest energy cosmic rays, a longstanding mystery in particle astrophysics. Previous searches for neutrino production have been performed by the IceCube (Abbasi et al. 2010, 2011) and RICE collaborations (Besson et al. 2007), but this is the first search for UHE neutrinos from GRBs above 10^9 GeV.

2. THE ANITA INSTRUMENT

A full description of the ANITA-I instrument can be found in Gorham et al. (2009), and a description of instrument modifications for ANITA-II is in Vieregg (2010) and Gorham et al. (2010). Briefly, the ANITA experiment is a NASA Long Duration Balloon experiment that searches for coherent, impulsive, broadband radio emission (200-1200 MHz) from electromagnetic showers induced by UHE neutrinos interacting in the Antarctic ice sheet (Gorham et al. 2009; Askaryan 1962). The second flight of the ANITA experiment launched on 2008 December 21, flew for 31 days, 28.5 of which were live days, and recorded over 26 million triggers. Forty quadruped, dual-polarization horn antennas search for radio impulses which could be caused by neutrino interactions in the ice sheet. The trigger requires coherent power in neighboring antennas, and the threshold is limited by thermal-noise emission from the ice. Over 98.5% of recorded events were fluctuations of thermal noise. The trigger is designed to optimize efficiency on neutrino-like signals: vertically-polarized, broadband impulses. Signals from each polarization of each antenna are recorded in a 100 ns window for each triggered event, allowing for directional determination on an event-by-event basis us-

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ing interferometric techniques, also described at length in Gorham et al. (2009). ANITA is most sensitive to neutrinos which come from between the horizon and a payload elevation angle (angle above the horizontal) of -25° .

3. DATA ANALYSIS

We are able to construct a more sensitive search for UHE neutrinos from GRBs compared to the previously reported diffuse UHE neutrino search with ANITA-II (Gorham et al. 2010) because the short time window given by the burst duration dramatically reduces background in the signal region, allowing us to lower our analysis threshold and look for very weak signals which also have a time and direction correlation with the observed GRB.

There are two sources of background for an ANITA neutrino search. The first is thermal-noise fluctuations, which are easily removed with a set of cuts on the strength of waveform correlation among neighboring antennas and the signal strength. The second is man-made noise, which can be removed because it tends to cluster with locations of known human activity and with other events. The details of event reconstruction, thermal-noise rejection, and man-made noise rejection are discussed in Vieregge (2010) and Gorham et al. (2010). Compared to the diffuse neutrino search, we loosen numerical values of thermal-noise cuts. The cuts against man-made noise remain the same.

Any prompt emission neutrino candidate events would be vertically-polarized events which occur during the GRB prompt emission window (T_{90} , the time over which 90% of gamma-rays were detected), pass thermal-noise cuts, and are hardware-triggered in the direction of the observed GRB ($\pm 22.5^\circ$). Events are also rejected if they cluster with man-made noise (identified in the previous UHE neutrino search analysis (Gorham et al. 2010)) or with locations of known human activity on the Antarctic continent. We also searched for precursor neutrino emission in the 100 seconds before the start of the burst (Razzaque et al. 2003).

We proceed in the search for GRB-coincident neutrinos using a blind method. We set all analysis cuts on regions of time which should contain no neutrino events, and then apply the same cuts in the prompt and precursor emission windows. For the purpose of setting analysis cuts, we chose the 55 minutes starting 1 hour before each burst and the 55 minutes starting 5 minutes after the burst (for a total of 1 hour and 50 minutes) to be the background period for the burst. This allows us to use events close to the signal region in time as a background sample without ruling out the possibility of extended prompt or precursor neutrino emission.

Of the 26 bursts observed by Swift or Fermi during the flight of ANITA-II, only 12 bursts had background periods with a thermal-like distribution of events. Information from the Gamma-ray bursts Coordinates Network (GCN, NASA (2011)) about these 12 bursts is in Table 1. The remaining 14 bursts had significant anthropogenic activity in the background periods, and were removed from the analysis to reduce the risk of man-made events occurring during the signal time window. Figure 1 shows the location of the ANITA payload when each of the 26 GRBs occurred. The green circles indi-

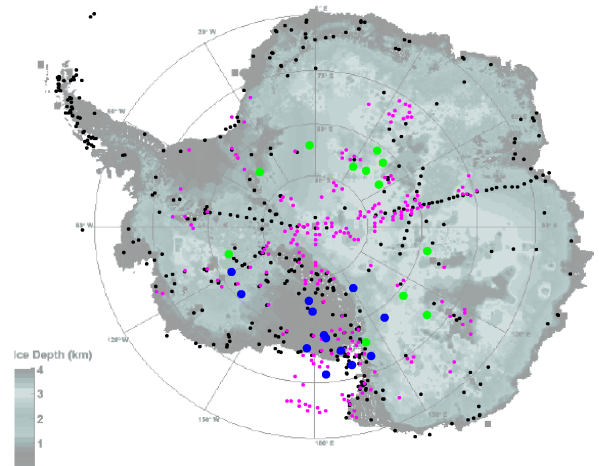


FIG. 1.— The location of the ANITA payload during each of the 26 bursts recorded during the flight of ANITA-II. Green locations are bursts with clean background periods, and blue locations are bursts with anthropogenic noise in the background periods. Locations of human activity are shown in black (known) and magenta (possible).

cate bursts with clean background periods, while the blue circles indicate bursts with noisy background periods. As expected, the bursts with noisy background periods are from times when the payload is near McMurdo station and the Ross Ice Shelf, the part of the continent with the most human activity.

We set the analysis cuts so that if one event were found in the prompt emission signal region for any burst, it would be a three sigma fluctuation of the expected background. We set the final analysis cut (on the peak value of the cross-correlation from the interferometric image, described in Gorham et al. (2010)) to allow 0.0044 background events in the total prompt signal region for all 12 bursts. The final analysis cuts used in this search are over 98% efficient for events which trigger, even for the smallest low-SNR triggered signals, when tested on signal-like calibration events from a radio-frequency pulsing station at Taylor Dome.

4. RESULTS

We found no events in the blind signal region for prompt emission (T_{90}). We also found no events in the precursor window (100 s before the start of each burst). This is consistent with the background expectation. We proceed to set a limit for each burst individually on the prompt UHE neutrino fluence using a Feldman-Cousins 90% confidence interval, the duration of the burst, and the acceptance calculated using an ANITA Monte Carlo simulation. For each GRB, we configured the Monte Carlo to simulate a point source at the location of the burst, fixed ANITA at the location of the payload during the burst, and assumed an input E^{-4} spectrum. We investigate systematic effects on the ANITA-II diffuse neutrino limit due to uncertainties in neutrino cross section, surface roughness, and birefringence in Gorham et al. (2010), and the limit presented here would be affected by approximately the same factor, $\sim 10\%$.

Table 2 contains the calculated synchrotron break energy (where the spectrum turns from E^{-2} to E^{-4}), as well as predicted fluxes beyond the break for each of the 12 GRBs used in this search. The calculations fol-

TABLE 1
LIST OF THE 12 GRBs INCLUDED IN THE BLIND ANALYSIS

GRB	Date & Time (UTC)	Right Ascension	Declination	Payload Elevation Angle (degrees)
081228	2008 Dec 28 01:17:40	2 ^h 37 ^m 50 ^s .94	30°51'10 50''	-41.1
081229	2008 Dec 29 04:29:01.88	11 ^h 22 ^m 0 ^s	55°6'0''	-55.9
081230	2008 Dec 30 20:36:12	2 ^h 29 ^m 19 ^s .51	-25°8'49 95''	28.8
081231	2008 Dec 31 03:21:01.93	14 ^h 35 ^m 0 ^s	-38°43'0''	47.0
090102	2009 Jan 2 02:55:36	8 ^h 32 ^m 58 ^s .54	33°6'51 10''	-26.3
090108B	2009 Jan 8 07:43:23.36	0 ^h 15 ^m 0 ^s	-32°12'0''	42.9
090109	2009 Jan 9 07:58:29.49	8 ^h 11 ^m 0 ^s	54°48'0''	-59.2
090111	2009 Jan 11 23:58:21	16 ^h 46 ^m 42 ^s .14	0°4'38 21''	1.7
090112A	2009 Jan 12 07:57:23.11	7 ^h 27 ^m 0 ^s	-30°17'0''	23.5
090112B	2009 Jan 12 17:30:15.45	12 ^h 51 ^m 0 ^s	22°12'0''	-26.8
090113	2009 Jan 13 18:40:39	2 ^h 8 ^m 13 ^s .63	33°25'42 85''	-25.7
090117B	2009 Jan 17 08:02:02.23	15 ^h 32 ^m 0 ^s	27°36'0''	-28.1

low methods in Besson et al. (2007), which are based on Waxman-Bahcall calculations (Waxman & Bahcall 1997, 1999, 2000; Waxman 2003). Redshift and gamma-ray flux information are available from the GCN (NASA 2011). For bursts with no redshift information, we use a redshift of $z = 2$ for flux calculations, following Abbasi et al. (2010). For all bursts, the UHE regime is well past the break energy, leading to an E^{-4} spectrum over the entire ANITA energy range.

There are two ways that ANITA can view the radio emission from a neutrino interacting in the ice. The first geometry, called a *direct* observation, occurs when ANITA observes the radio impulse directly from the interaction of an upgoing neutrino. The second geometry, called a *reflected* observation, occurs when ANITA sees the radio impulse reflected off of the bottom of an ice shelf (at the sea water interface) from the interaction of a downgoing neutrino. Since UHE neutrinos are absorbed as they travel through the Earth, most of ANITA's direct events would be associated with neutrinos which skim across the ice. When ANITA is over the Ross Ice Shelf, it can also make a reflected observation of downgoing neutrinos.

None of the 26 GRBs during the flight had a payload elevation angle between -25° and the horizon, which is where ANITA has the best chance of seeing direct neutrino events. Of the 12 GRBs used in this search, the most promising direct observation geometry was from GRB090113 (an elevation angle of -25.7°). The 90% confidence level fluence limit for energies $10^8 \text{ GeV} < E < 10^{12} \text{ GeV}$ is $E^4\Phi = 1.5 \times 10^{20} \text{ GeV}^3\text{cm}^{-2}$ from GRB090113, shown with the dark red line in Figure 2. Although the limit from GRB090113 is the best direct observation limit from ANITA-II, it still suffers from poor geometry. If the burst had oc-

curred at the angle of maximum sensitivity of ANITA-II (-10° in elevation), the fluence limit would have been $E^4\Phi = 5.2 \times 10^{16} \text{ GeV}^3\text{cm}^{-2}$.

There was one downgoing burst (GRB090107A) at an elevation angle of 0.5° which occurred while ANITA-II was over the Ross Ice Shelf, allowing for a reflected observation¹¹. Because of ANITA's proximity to McMurdo station during this burst, the background period had significant anthropogenic noise and the burst was excluded from the sensitive analysis described here. However, if we use the same analysis cuts as in the blind diffuse UHE neutrino search described in Gorham et al. (2010), we observe 0 events in the prompt and precursor emission window for this burst. Although the search sensitivity is worse for this burst because we did not loosen the thermal-noise and man-made noise cuts as described above, the observation of 0 events from this burst still leads to the best limit from ANITA-II on the UHE neutrino fluence from gamma-ray bursts, $E^4\Phi = 2.5 \times 10^{17} \text{ GeV}^3\text{cm}^{-2}$, shown in blue in Figure 2.

5. CONCLUSIONS

We have used the temporal information of GRBs which occurred during the flight of ANITA-II to search for co-incident prompt and precursor neutrino emission with greatly reduced background and improved threshold relative to previous UHE astrophysical neutrino searches with ANITA. While the expected fluence based on the standard models of GRB particle production is too low to have expected a detection, we present the first limits on GRB neutrino fluence for energies above 10^9 GeV . There is room for about a factor of five improvement with ANITA-III if a GRB occurs with a good geometry relative to the payload.

REFERENCES

- Abbasi, R., et al. 2010, ApJ 710, 346-359
 Abbasi, R., et al. 2011, arXiv:1101.1448
 Alvarez-Muñiz, J. & Halzen, F. 1999, ApJ 521, 928
 Askaryan, G. 1962, JETP 14, 441
 Becker, J. 2008, Phys. Rept. 458, 173-246
 Besson, D., et al. 2007, Astropart. Phys. 26, 367-377
 Dermer, C. D. & Atoyan, A. 2006, New J. Phys. 8, 122
 GCN: The Gamma-ray bursts Coordinates Network, <http://gcn.gsfc.nasa.gov/>
 Gorham, P., et al. 2009, Astropart. Phys. 32, 10
 Gorham, P., et al. 2010, Phys. Rev. D 82, 022004; arXiv:1011.5004
 Guetta, D., et al. 2004, Astropart. Phys. 20, 429
 Halzen, F. & Hooper, D. 2002, Rept. Prog. Phys. 65, 1025
 Meszaros, P. 2001, Science 291, 79

¹¹ GRB090107A occurred on 2009 January 07 at 04:48:04 UTC, with a right ascension of 20^h9^m38^s.16 and a declination of 4°44'38 40'' (NASA 2011). The calculated synchrotron break energy is $1.27 \times 10^7 \text{ GeV}$ and the flux above the break energy is $E^4\Phi = 9.53 \times 10^6 \text{ GeV}^3\text{cm}^{-2}\text{s}^{-1}$

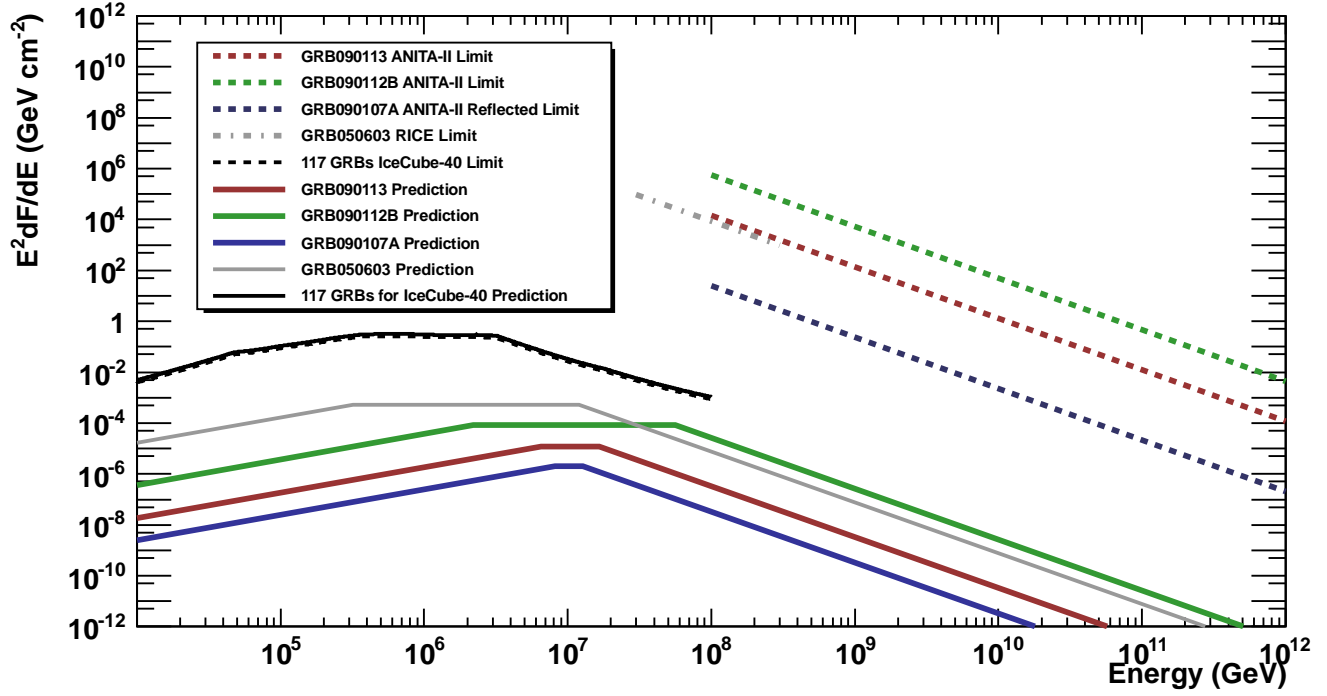


FIG. 2.— The two best direct limits on the UHE neutrino fluence from the blind analysis are from GRB090113 and GRB090112B, and are shown with red and green dashed lines respectively. The best reflected limit is from GRB090107A, shown with a blue dashed line. RICE (Besson et al. 2007) and IceCube (Abbasi et al. 2011) limits are also shown. The IceCube limit is an aggregate limit based on 117 individual GRBs, and is based on a fluence prediction from Guetta et al. (2004).

TABLE 2
BREAK ENERGIES AND TOTAL FLUX IN THE UHE REGIME
CALCULATED FOR THE 12 BURSTS IN THE BLIND ANALYSIS

GRB	z	Synchrotron Break Energy (GeV)	$E^4 \Phi$ ($\text{GeV}^3 \text{cm}^{-2} \text{s}^{-1}$)
081228	3.8	2.18×10^7	2.63×10^8
081229	-	7.93×10^7	8.53×10^{10}
081230	-	1.09×10^7	3.03×10^7
081231	-	5.47×10^7	1.93×10^{10}
090102	1.55	1.10×10^6	4.29×10^3
090108B	-	7.55×10^7	7.03×10^{10}
090109	-	4.18×10^7	6.60×10^9
090111	-	1.22×10^7	4.81×10^7
090112A	-	2.40×10^7	7.21×10^8
090112B	-	5.59×10^7	2.12×10^{10}
090113	-	1.66×10^7	1.63×10^8
090117B	-	2.37×10^7	6.81×10^8

- Meszaros, P. 2002, *Ann. Rev. Astron. Astrophys.* 40, 137
 Meszaros, P. & Rees, M. 1993, *ApJ* 405, 278
 Razzaque, S., *et al.* 2003, *Phys. Rev. D* 68, 083001
 Vieregg, A. G. 2010, PhD Dissertation, University of California, Los Angeles
 Waxman, E. 2003, *Nucl. Phys. B Proc. Suppl.* 118, 353
 Waxman, E. & Bahcall, J. 1997, *Phys. Rev. Lett.* 78, 2292
 Waxman, E. & Bahcall, J. 1999, *Phys. Rev. D* 59, 023002
 Waxman, E. & Bahcall, J. 2000, *ApJ* 541, 707
 Wick, S. D., Dermer, C. D., & Atoyan, A. 2004, *Astropart. Phys.* 21, 125